THE PATH TOWARDS A GERMANE SAFETY AND LICENSING APPROACH FOR MODULAR HIGH TEMPERATURE GAS-COOLED REACTORS

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ABSTRACT

Licensing is often singled out as one of the main challenges, and often also as a hindrance, to the deployment of new advanced reactors. The time to obtain design certification or a construction license, and especially the substantial costs involved, are often highlighted as contributing factors to the lack of progress made towards the near-term deployment of these advanced designs. These new reactors often claim to have enhanced safety characteristics compared to the current fleet of nuclear power plants, and therefore also claim that a simplified safety evaluation and licensing process should be applied. One of these advanced nuclear power systems are high temperature gas cooled reactors that indeed possess many salient and inherent safety characteristics. Supporters of the technology have for a long time been advocates that a different licensing approach and therefore also a different set of safety requirements should be developed and applied. A short summary of the safety design approach used is provided. This leads into comments on some of the historical licensing experiences and the status of current initiatives to facilitate the development of new safety requirements. More details are provided on the status of the IAEA cooperative research project and status on the approaches that can be followed to develop germane safety design criteria.

1 Introduction

After nearly 60 years the nuclear power industry is today dominated by water cooled reactors (WCRs). It is therefore also natural that most of the world's nuclear licensing authorities, and also the activities of the International Atomic Energy Agency (IAEA), are focused on WCRs. It follows logically that the IAEA safety requirements [1,2] are also largely developed for these nuclear power plants (NPP).

High Temperature Gas Cooled Reactors (HTGRs) is one of the advanced nuclear power systems considered for the future and also one of the systems included in the Generation IV Forum [3]. As so many other advanced reactors technologies considered for deployment, the basic concept is not new and prototype HTGR power plants have been licensed, built and operated in the past. The last two prototype nuclear power plants, Fort St. Vrain (in the USA) and the THTR-300 (in Germany), were however both shutdown in the 1980's. So the question should be asked why the topic of a safety and licensing approach need to be raised when this type of plant has been licensed before. The answer is two-fold: In the last 30 years the safety and licensing requirements have been strengthened substantially but in the process it also became more light water reactors (LWR) technology specific with the consequence that it is more difficult to interpret and apply to HTGRs. The second is the change in the safety philosophy used in all modern HTGR designs where many of the safety systems required in LWRs is made obsolete. More discussion on the approach and safety characteristics of modular HTGRs are included in Section 2.

In the last few years more calls have been made that a new approach should be developed and followed to allow licensing of advanced reactors, especially in the USA. Efforts to develop HTGR specific safety requirements have also started. In South Africa the National Nuclear Regulator (NNR) established several pebble bed specific requirement documents and the US-NRC, in cooperation with the US-DOE, have developed and proposed general design requirements for HTGRs. Some information is provided in Section 3.

Some efforts have been made over the years to develop a germane safety and licensing approach for HTGRs. Historically most of these efforts used the well-known LWR safety requirements as the starting point and then introduced interpretations or exceptions for HTGRs. This approach is hugely based on engineering judgement and expert opinion. This approach was followed in the case of past operating HTGRs and also more recently in the licensing of the HTR-PM, under construction in China. A more fundamental approach, that requires a detailed plant design and thus a substantial effort, has also been proposed. In this approach safety functions are assigned to systems, structures and components for the specific design and then high level safety requirements are derived. Both of these approached are followed in an on-going IAEA Coordinated Research Project (CRP). This project is discussed in Section 4 and some examples of safety requirements are provided.

2 The modular safety approach

This principle of a modular design in HTGRs was first introduced by the designers of the HTR-Module in the 1980’s [4]. This design approach has been universally adapted in some form by the high temperature reactor community. The design must ensure that no early or large fission products release is possible under any credible event, including the total loss of the coolant. This drives the design features that lead to the following principles:

- use of high quality ceramic coated particle fuel that contains the vast majority of fission products to a very high temperature and for a long time (several hours) at these temperatures
- a long slender core with adequate heat loss through the reactor outer structures so that decay heat is removed by all-natural means relying only on radiation, conduction and convection and with no need for the coolant to be present
- a low power density so that the fuel temperature rise is limited in an event where all active cooling and coolant are lost, so that the maximum fuel temperature will, with some margin, remain below a value where most fission products are contained in the coated particles
- use of an inert coolant such as helium with no phase changes, no heat transfer limits and with insignificant neutronic interactions
- strong negative temperature reactivity feedback coefficients
- relative large core with ceramic core internals that have a large heat capacity that lead to slow response times and thus long and gradual temperature transients

One very important characteristic of the coated particle (CP) fuel and fission product retention in HTGRs is worth highlighting: “The failure mechanisms of CP fuel are decoupled and totally independent. One coated particle failure cannot lead to the failure of a neighboring CP, as it is driven by the maximum fuel temperature. A CP failure also has no effect on the cool-ability of the fuel as a failure will not change the heat removal path. The amount of fission products that can potentially be release when a failure occurs is of course very small, and many CP will need to fail to be of any consequence. In this respect it is very different from WCR fuel where one pin failure can inhibit the cooling of neighbors and cause significant additional failures or a partial core melt.” [5].

In contrast the argument is quite different for WCRs as highlighted by Carlson et.al in reference [6]: “The safety terrains of today’s operating light water reactors (LWRs) are generally well understood. They are terrains that can be reasonably described as featuring a number of cascading “cliff edge” effects (e.g., core uncovery leading to massive core damage, vessel failure, and containment breach). Such cascading effects have long been predicted to appear over a range of postulated severe events and most notably did appear in the historic events of the Fukushima Daiichi accident of March 2011."

When applying the design principles for modular HTGRs it results in NPP designs where no active cooling or safety systems are required to perform decay heat removal. The helium coolant also does not need to be present. This then further excludes the need for cooling and coolant injection systems, the need for secured emergency power (in the case of station black-out), or the need for severe accident mitigation systems (like a core catcher) introduced in other designs in case the engineered decay heat removal safety systems fails. For modular HTGRs the residual heat removal is ensured solely through physical processes (thermal conduction, radiation, convection) and concepts such as core melt of severe core damage is not appropriate.

The modular HTGR design approach also incorporates many of the lessons learned from the earlier (typically higher power) designs. For example the large core diameter of the THTR-300 core required in-core control and shutdown rods, a design that lead to damaged fuel spheres. A smaller diameter core allows control and shutdown of the reactor with neutrons absorbers located only in the outer reflectors. The larger power reactors also required active cooling to remove decay heat and maintain acceptable vessel temperatures (pre-stressed concrete in many designs). The move has therefore been towards smaller reactor units (100-600 MW_{th}) that can be deployed as a multi-module power plant if higher output is required.

The HTGR designs also face other design and safety challenges. The two postulated accidents that may lead to a significant increase in the fission product release from the core is water ingress and massive air ingress with the consequential graphite oxidation that may expose the coated particle fuel. As in the case of other technologies design choices are made to prevent or limit the consequences of these effects. The amount of water that may leak into the core from the steam generator can be limited but water vapour will lead to additional release of fission products from fuel, especially from any damaged coated particles. The "diving bell" concept was used in the HTR-Module [4] design to limit any large penetrations at the top of the reactor and thus to prevent any chimney effects in case of a primary helium pressure boundary failure and air ingress.

From the few examples discussed in this section it should be clear that the physical phenomena and safety approach for modular HTGRs are substantially different from that of the current fleet of WCRs. This should be enough to warrant discussions and ultimately acceptance that HTGR specific safety requirements and licensing approach are needed. Many more examples can be given but all of these have been highlighted before. Perhaps the most controversial discussion and difference in opinion are normally around the need for containment (not the containment function that is clearly required but rather the containment structure). Some more words on this later.

3 Licensing experience

Several prototype and demonstration HTGRs were built and operated as shown in Fig 1. It started with the Dragon project, an OECD project hosted by UK, followed shortly after with the AVR and Peach Bottom reactors. These early prototypes were followed by two larger demonstration plants, the Fort St Vrain in the USA and the THTR in Germany. More licensing information are available for these later demonstration plants [7,8]. The lessons learned during licensing clearly pointed towards the need for HTGR specific requirements and specifically that the coated particle fuel and its ability to contain fission products to high temperatures (and for an extended period of time) should be acknowledged. These reactors already demonstrated some of the safety principles and the large safety margins inherent in gas-cooled reactor technology.

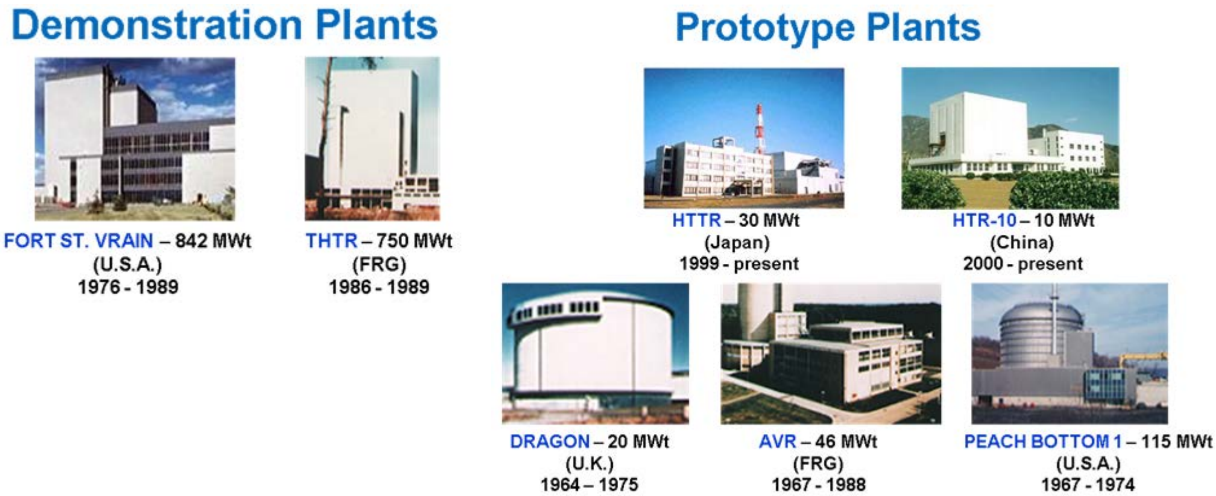

Fig 1. The built and operated HTGR prototype and demonstration plants (past and present)

Today two smaller test reactors are still available, the HTTR in Japan and the HTR-10 in China. The licensing and operations of these reactors, especially with all the safety demonstrations already performed and planned, are making a significant contribution to the licensing efforts of future NPPs. The licensing and experience gained with the HTR-10 test reactor were excellent preparation for both the designers and regulators to prepare for the licensing of the commercial demonstration plant. The Preliminary Safety Analysis Report (PSAR) for the HTR-PM has been reviewed and accepted and construction has started in December 2012. The FSAR is being finalised and commercial operation is planned in 2018.

Other noteworthy licensing experience are available from the efforts to license the HTR Module (late 1980's) in Germany [8], the South African Pebble Bed Modular Reactor (PBMR) project from 1999 to 2010 [9-10], and licensing preparation activities with the NRC, USA that started as part of the PBMR and Next Generation Nuclear Plant (NGNP) project [11]. In the USA these efforts have now led to the release of draft advanced non-light water reactor design criteria [12], including specific criteria for HTGRs. The proposed general design criteria (GDCs) already reflect due consideration of the HTGR specific safety characteristics. These include concepts such as functional containment, a move away from the LWR emphasis on loss of cooling accidents (LOCAs), specifically mention of air and water ingress, and a distinction made between fuel design limits (LWRs) and core radionuclide release limits that takes the behaviour of coated particle fuel into account.

The IAEA has also published and performed activities in the past to develop technology neutral but also HTGR specific guidance. A selection of this is referenced [13-16]. More recently the IAEA initiated a CRP to develop safety design criteria for a modular HTGR. This activity is described in the next section.

4 The IAEA coordinated research project

The IAEA has launched the CRP on Modular High Temperature Gas-cooled Reactor Safety Design in 2014 to investigate the development of new safety design criteria [5,17]. The participating member states are China, Germany, Indonesia, Kazakhstan, Korea (Republic of), Japan, Ukraine, UK and the USA. This project is coordinated by the Nuclear Energy Department of the IAEA (not the department responsible for safety requirements) and the final reports from this project will reflect the wishes and proposals of the participating member states on this matter. It will not have the status of an official IAEA safety requirement document since this requires a comprehensive process of drafting and review that typically takes several years to acquire [2]. The project thus largely reflects the perspectives of the designers and safety analysts. The outcome of this project could be a valuable start towards the goal to develop official HTGR safety design requirements.

Two approaches are followed as demonstrated in Fig 2. In the first approach the participants are developing and applying a safety design process to specific reactor designs. From this exercise the required safety functions will be assigned to systems that will then be use to derive the high level requirements (a bottom-up approach). In the second approach the current WCR requirements are used as the basis and through engineering judgement and other considerations amendments to the current requirements are proposed. The final outcome will of course be compared with the current safety requirements and also verified against the fundamental safety functions, and ultimately also the safety of the public and workers by dose limits.

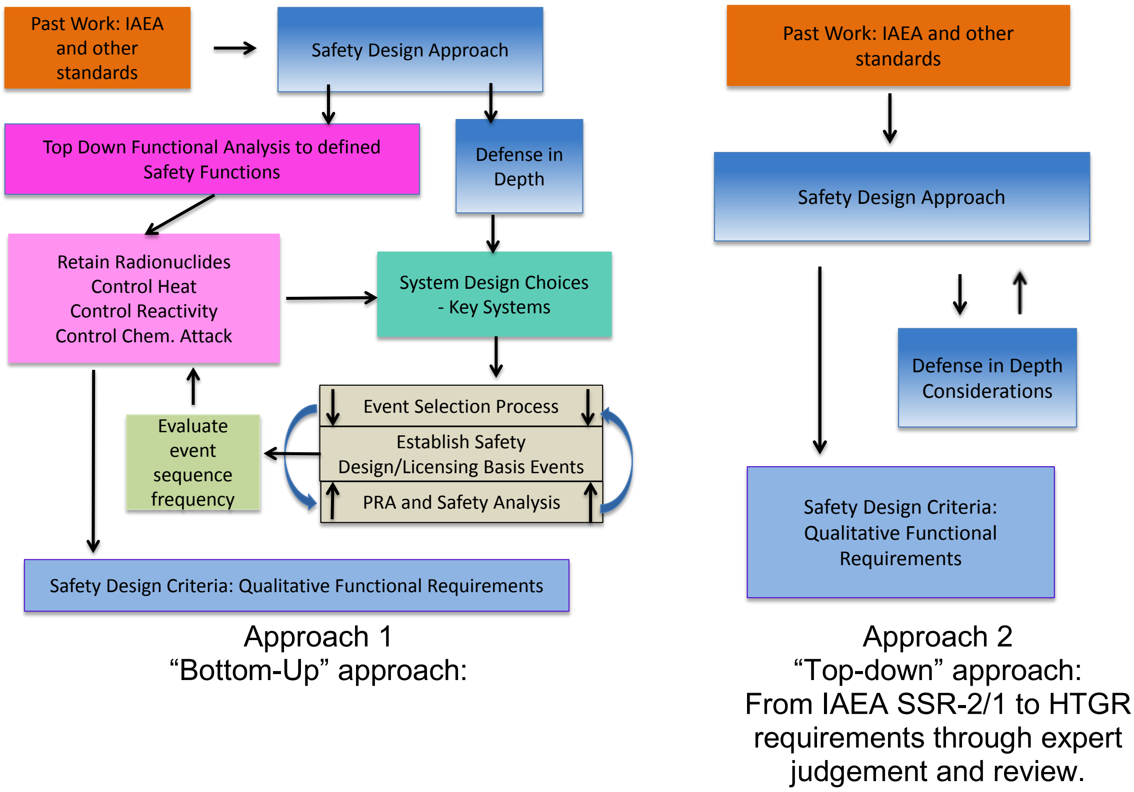

Fig 2. The two approaches followed to define safety design criteria

Examples of non-applicable requirements from the IAEA Specific Safety Requirements No. SSR-2/1 Safety of Nuclear Power Plants: Design include:

- safety concepts such as design extension conditions "with core melting" is not applicable to HTGRs and need alternative interpretations or ideally alternative definition of plant states, design basis and beyond design basis accident conditions
- specific requirements on fuel need new interpretations especially for pebble bed type fuel since concepts such as fuel pin, cladding and fuel assembly is not defined. Also pebbles fuel are much more robust and handled quite differently and is for example designed to be dropped into the core and spent fuel storage
- the focus of the requirements on the containment function and structures needs to stress the dominant role played by the coated particle fuel as the most important barrier to fission product release. HTGRs lack the "cascading cliff edge effects" [6] and the requirements of multiple barriers and the implementation of defense in depth should be considered carefully, but also clearly differently.
- since the gas coolant is not condensable a helium pressure boundary failure and release into a leak-tight containment will result in a sustained elevated pressure condition since the pressure cannot be reduced by cooldown. A pressurized containment condition will act as a driving force to transport radioactivity into the environment in case of a failure. In the case of CP fuel no large early release is

expected but the delayed release, due to fuel and core heat up, can potentially be larger. It is thus generally accepted that early pressure release is preferable.

- requirements on chemical attack, especially on massive air ingress, should be added in order to strengthen the safety requirements
- since HTGRs are ideal for high temperature process heat applications and cogeneration, specific attention needs to be given to co-located facilities (such as a chemical plant) as well as multi-module considerations and aspects such as connectivity and shared systems.

The comprehensive and duel approach followed in the CRP should lead to well defined and a germane set of safety design criteria that does not only take the specific safety characteristics into account, but has also through the exercise been implemented and tested for actual example modular HTGR designs.

5 Concluding remarks

The need to develop HTGR specific safety requirements are well recognised by the HTGR community. Two different approaches are being followed in the IAEA CRP on modular HTGR safety design to provide guidance to member states and safety authorities. It is still not clear if the two approaches followed in the CRP will lead to the same requirements or if they will be complementary.

It is hoped that the CRP reports and recommendations could lead to the development of official HTGR-specific safety requirements or guidance documents by the safety department of the IAEA. Alternatively, the development of safety requirements for advanced reactor systems may be developed with the aim to be technology neutral. Past efforts towards this goal [16] have proven to be quite challenging. It can only be practically achieved if new specific definitions and interpretations are used for the non-LWR designs or the technology-neutral design requirements need to be defined only at a very high level; in which case guidance for the implementation of the different technologies will again be required.

The path to a germane safety and licensing approach for HTGRs may be quite different depending on the member state where it is deployed. An approach to follow LWR requirements and then agree to the specific exceptions and additional design criteria can clearly be implemented as was the case in Germany before and recently again, when this same approach was followed in China for the HTR-PM licensing. In both cases the nuclear regulator were already experienced in the technology when these applications were considered. In Germany the AVR and THTR-300 reactors preceded the HTR-Module license evaluation and in China the HTR-10 test reactor has been licensed and operated for several years. The potential success of this approach thus depends on past experience and the type of licensing approach used (prescriptive or not).

A more ambitious path is sometimes also discussed within the community. This requires the development of a new safety and licensing approach based on the fundamental reactor characteristics and phenomena. This is the process that took the last 60 years to be developed for WCRs. Although it is inconceivable to repeat this for HTGRs or other advanced technologies, some practical proposals have been made to at least reconsider some fundamental aspects of the established approach and thus to transform it to be more appropriate. The “Approach 1” implemented in the CRP exercise and proposal to define a safety landscape [6] are two examples where this idea is already explored. This approach could also include the application of a graded approach that take the salient safety characteristics into account; but would also facilitate the “discovery” of new events or different terrains, where more focus and attention needs to be placed – for example the prevention of massive air ingress was already mentioned.

The ideal solution would be if the IAEA can establish safety requirements for advanced reactor technologies including specific guidance for HTGRs to be used by member states.

6 Disclaimer and Acknowledgement

The specific comments and ideas in this paper is that of the author alone and don't represent the official IAEA position on this topic. Some of the ideas are based on the discussions in the IAEA Coordinated Research Project Meetings held in 2015 and 2016. The participants in these meetings are acknowledged for their contributions.

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